# ORCLE ASE Phase II

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# Adaptive Spectral Encoding for Free Space Optical Communications

## Project Objectives

- Design and develop a multi-wavelength ASE transmitter and receiver E-O pair for FSOC
- Demonstrate ASE modem performance using 16 wavelength channels @2.5 Gb/s
- Use ASE modem in a field test to validate atmospheric obscurant mitigation
- Characterize pulse propagation through clouds
- Advanced multi-wavelength receiver arrays

## Technology Needs

- FSOC with atmospheric obscurant mitigation:
  - 2.5 Gb/s data rates
  - Clouds, fog, smoke, turbulence, aberrations
- Airborne/Ground platforms
- Capability to adapt to changing atmospheric conditions
- Added security at physical layer

## Key Innovation: Transmitter Architecture

## Technology Approach / Deliverables

**Approach**

- Evaluate and compare alternate approaches for transmitter modem and receiver modem designs
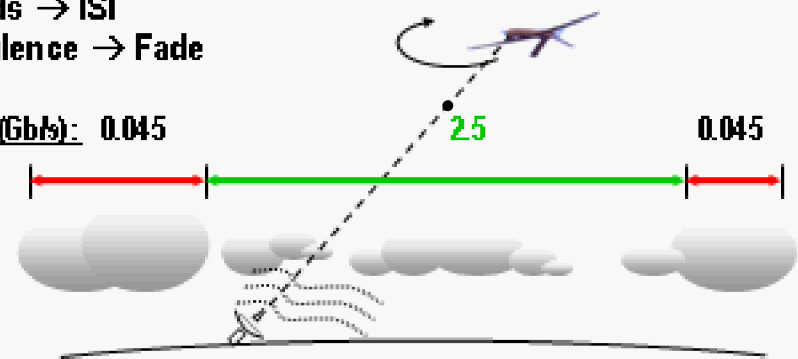- Downselect to one approach and develop breadboard transmitter modem and receiver modem

**Deliverables**

- Detailed characterization of pulse propagation through clouds
- Demonstrate ASE transceiver modem systems
- Demonstrate link through clouds
- Report on system performance

## ConOps

Clouds → ISI
Turbulence → Fade

DR (Gb/s):   0.045        2.5        0.045

# Summary of ORCLE ASE Phase I Results

- **Developed and demonstrated 2.5 Gbps, 16-wavelength agile transmitter**
  - Large signal noise due to broadband laser source
- **Developed 2.5 Gbps, 16-wavelength agile receiver**
  - Testing revealed need for renormalization circuitry to improve SNR
- *Initial* **pulse broadening measurements in cumulus clouds at 6,500 ft altitude:**
  - Turbulence-induced beam wander and thermal drift in optics near ground were problems
  - Looked for 180° scattering (largest pulse broadening) ⇨ *none was observed*
  - Large fluctuations in line-of sight attenuation vs time *were observed* ⟶
  - Need to characterize forward scatter angle and position
- **Models confirm absence of 180° scattering in cumulus clouds**
  - Strong forward scattering is well-documented
- *Conclusion:* **Approaches for improved laser com links in thin/intermittent clouds:**
  - Increase transceiver FOV; use non-line of sight scattering and wavelength encoding (ASE)
    ⇨ *Improve link robustness in the presence of clouds*
  - Narrowband, wide FOV filter
    ⇨ *Improve SNR performance of wide FOV data and acq/track receivers*
  - Minimize link re-acquisition time during total fades ⇨ *Optimize burst-mode average data rate*
    - No interleaver, tune up clock synch, exploit RF tracking feature of RF/EO transceivers

ASE Transmitter

Amplitude vs time
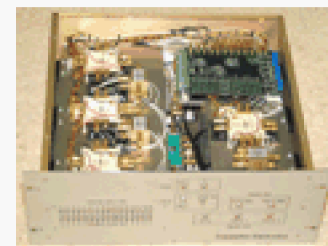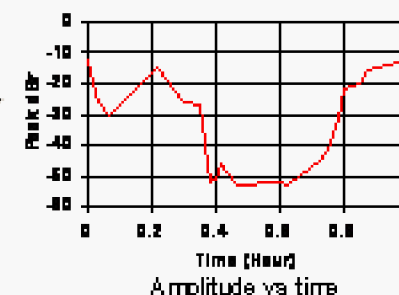
# Summary of Prior Cloud Pulse Broadening Data

- Subset of published data relevant to laser com
- Significant differences between prior data and ORCLE ASE plan:
  - Wavelength is much shorter (532 nm vs 1550 nm)
  - Cloud thickness / optical thickness range is too big ($\tau >> 10$): LOS attenuation $>> 10^{-4}$
  - Data does not allow calculation of radiance function for laser com receiver
  - Receiver designs impractical for laser com

| Expmt (Date) | Cloud Thickness (m) | Optical Thickness | Wavelength (nm) | FOV Half Angle (°) | Broadening (ns) | Comment |
|---|---|---|---|---|---|---|
| Mooradian et al (1979) | 960 | <18 23-26 | 532 | 7.5 | <20 60-100 | |
| Matter & Bradley (1981) | 765 | 8-20 | 532 | 0.5 | 8-12 | Off-axis receiver |
| Mooradian & Geller (1982) | 3000 | | 532 | 4.25 | 140 | Large (6 km) laser spot on cloud |

# Particle size/Wavelength Ratio Considerations

- Forward scatter component is reduced as the particle size gets smaller

- Water droplet scattering in air at 1.55 microns wavelength

- Cumulus cloud droplet radius is around 6 microns

- *A factor of three difference in wavelength is significant*
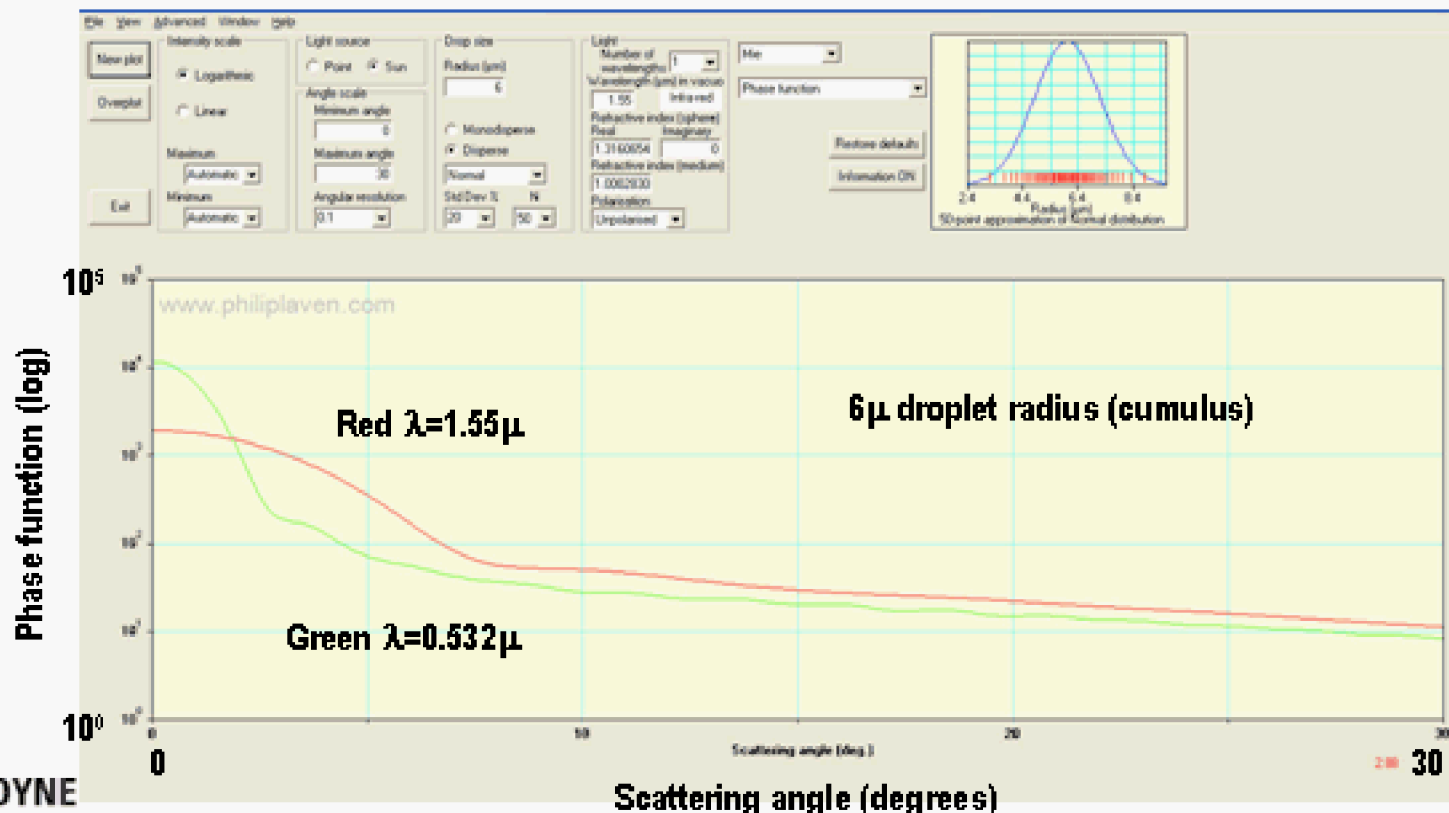
# Water and Fog-Oil Cloud Scattering Functions
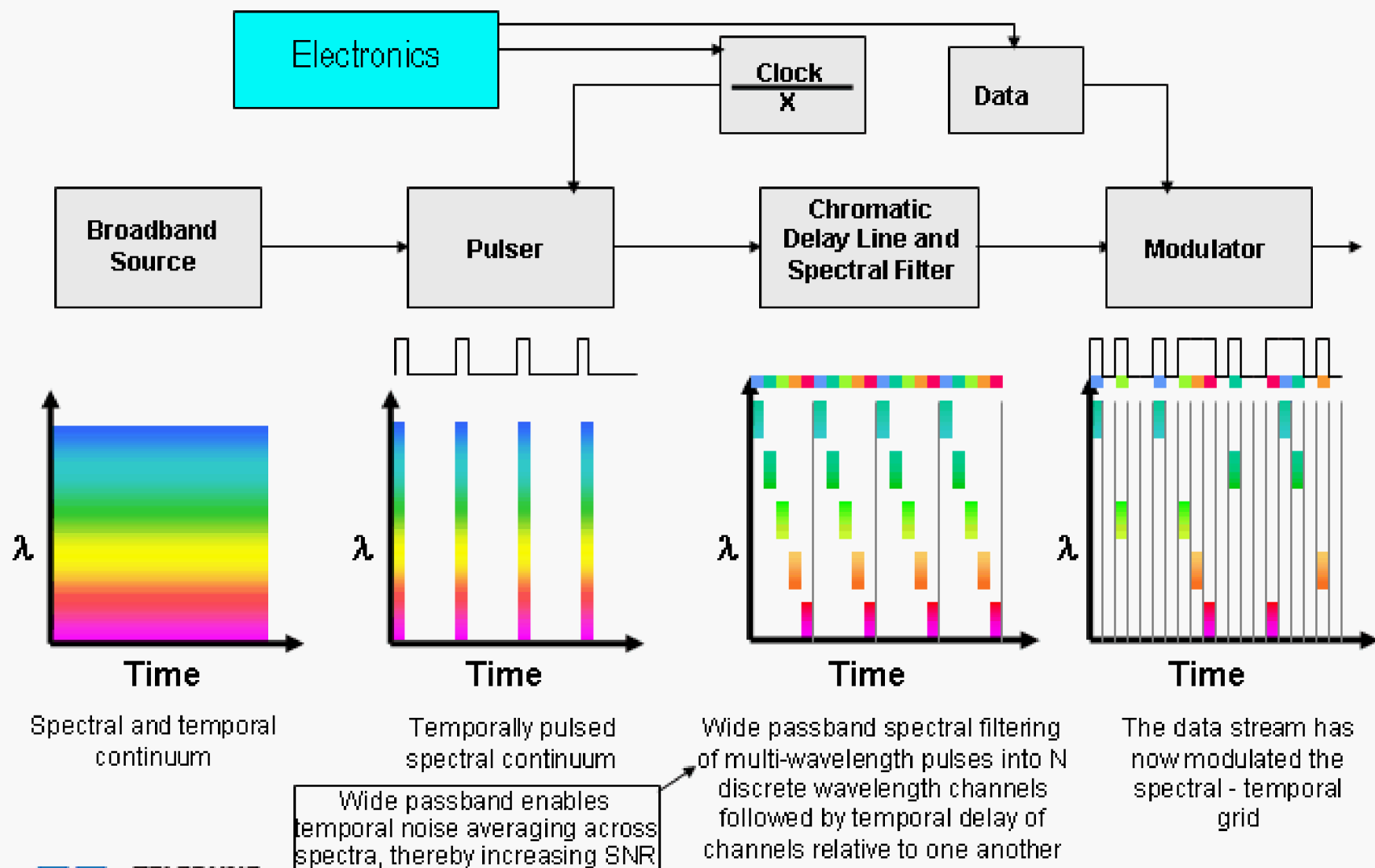## Mie Scattering Theory
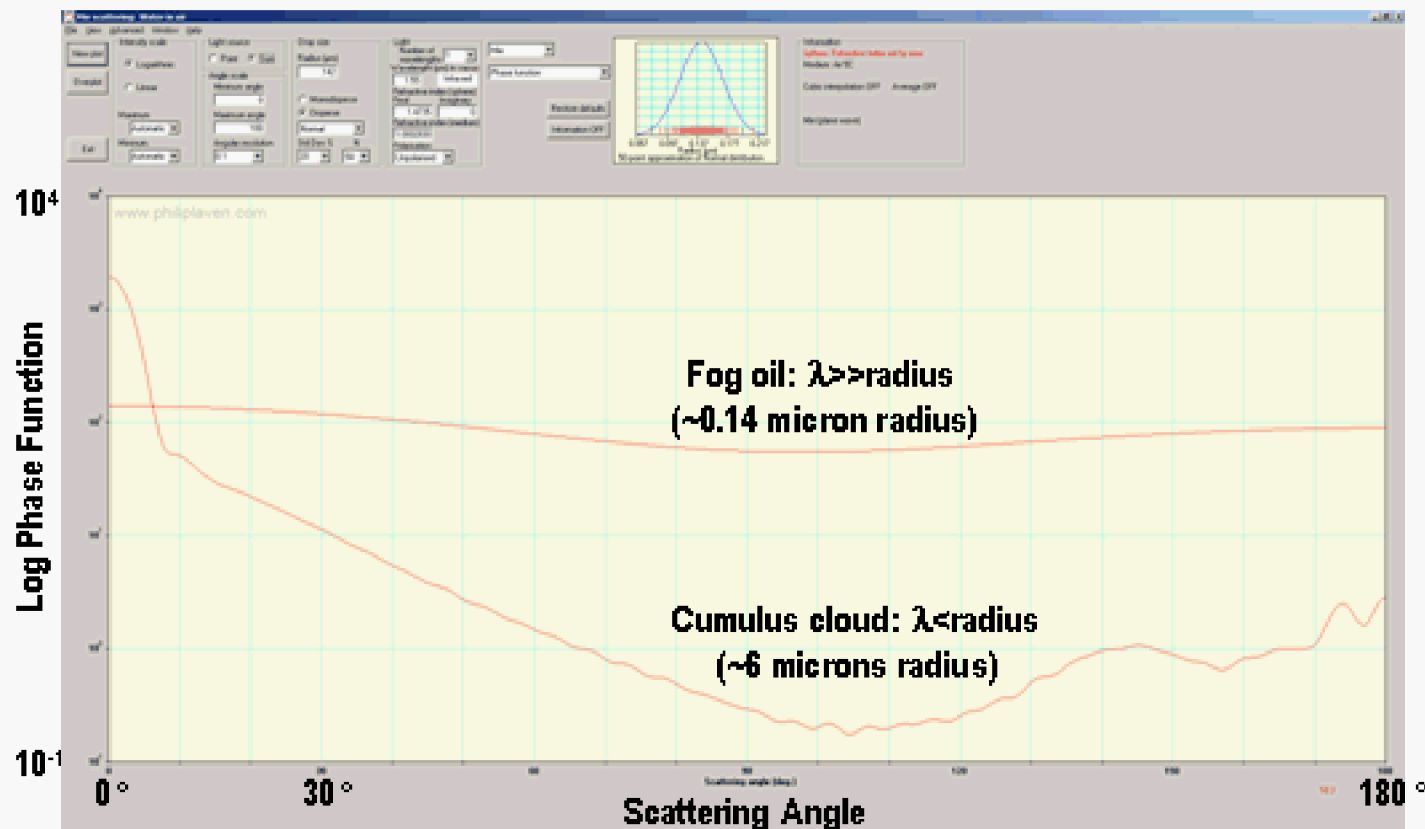


**Scattering is much more diffuse in fog oil than in water clouds**
- Water cloud scatter is much more strongly forward-scattered then fog-oil scatter
- Fog oil backscatter peak (180°) not much smaller than forward scatter peak

**Battlefield Obscurants program measurements will use ORCLE ASE equipment**

# Transmitter Modem Notional Design



Spectral and temporal continuum

Temporally pulsed spectral continuum

Wide passband enables temporal noise averaging across spectra, thereby increasing SNR

Wide passband spectral filtering of multi-wavelength pulses into N discrete wavelength channels followed by temporal delay of channels relative to one another

The data stream has now modulated the spectral - temporal grid

# Laser Com Scenario

- **Typical scenario for 11.3 km air-ground link:**

0.1 mr divergence        1 m        2° FOV

Tx      4°      36 m      Rx

10 km

0.5 km      1 km
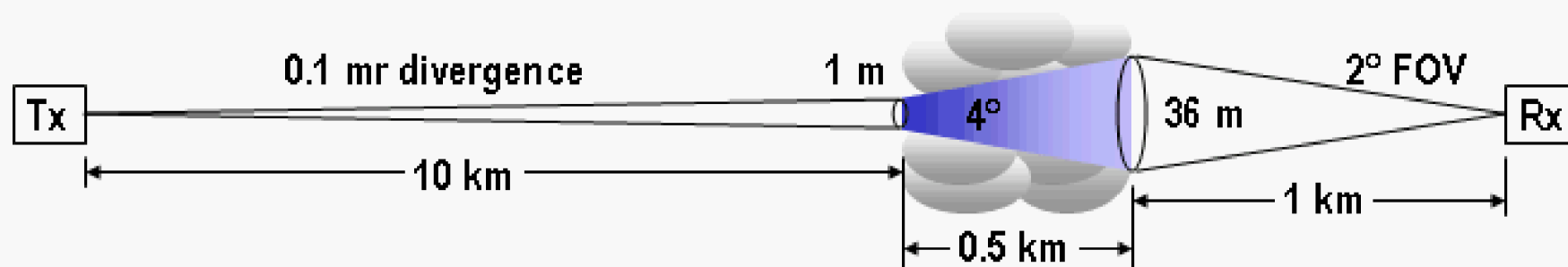
- **Corresponding cloud measurements:**

Rx

Tx    $\theta$    Rx    x

Tx          Rx

Scatter (FOV, x, $\theta$)

LOS Attenuation

$\dfrac{I_s}{I_{LOS}}$    FOV

$\tau$
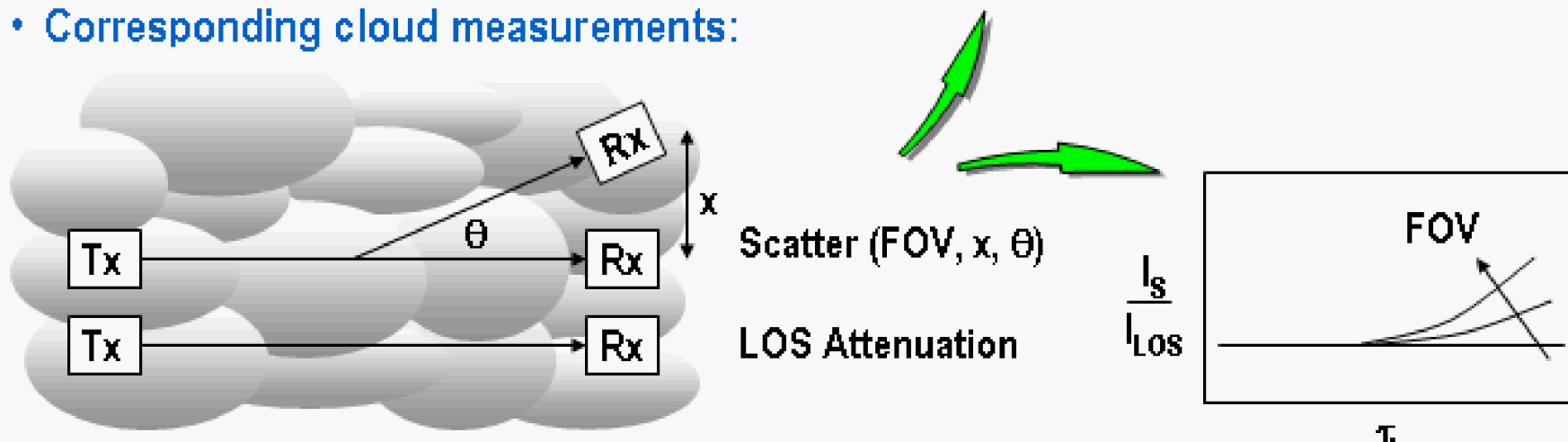
- **Pulse broadening can be calculated from radiance function**

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# Expected Pulse Broadening from Water-Cloud Scattering



Zero-scatterer path

One-scatterer path

Two-scatterer path, etc.
(all have the same path length)

$\theta_{fov}$

detector

Source (transmitter)

$\theta_{fov}$

L

Longest possible scatter paths are shown and compared to the shortest (LOS) distance
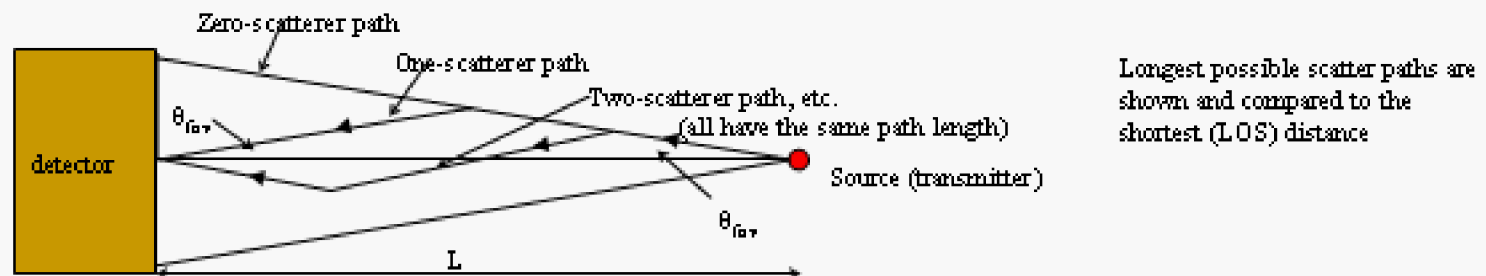
- Small-angle scattering approximation valid for water clouds where droplet size>>wavelength
- Only photons scattered by less than receiver FOV are detected
- Simple geometry gives maximum photon path length as $L(1/\cos(\theta_{FOV}) - 1)$



Pulse Broadening versus Receiver FOV (small-angle scatter approximation)

50 meter range
100 meter range
150 meter range

Maximum pulse stretching (nanoseconds)

Receiver FOV (degrees half angle)

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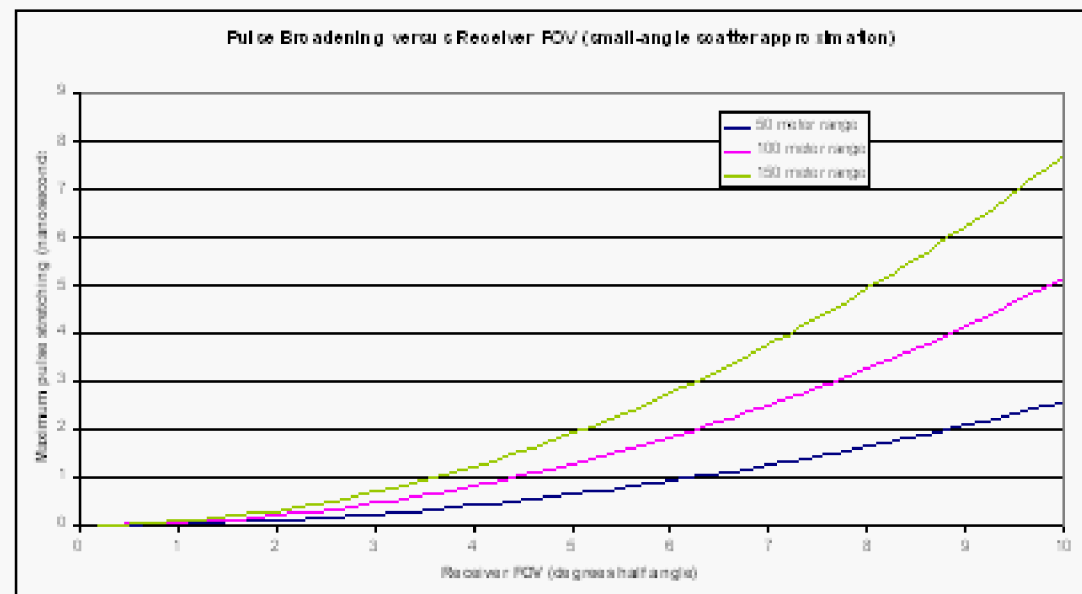
# ORCLE ASE Phase II Tasks

1. **Cloud Measurements** (initial focus of Phase II effort) **and Hardware Validation**
   - **Optical scattering experiments:**
     - Measure cloud transfer function
     - Characterize temporal fluctuations in line-of-sight attenuation
   - **Validation of ASE modem:** Use a bit error-rate (BER) tester to characterize ASE benefits

2. **Option 2: ASE Hardware Improvements**
   - **Improved light source:** Amplitude jitter from the broadband optical source limits system performance; an alternative multi-$\lambda$ source would substantially reduce this problem
     - Build a multiple laser source for bit error rate (BER) testing (meets near-term program needs)
     - Develop specifications for preferred laser source (leverage O-CDMA, OAWG, TACOTA, etc.)
   - **Implement normalization circuitry for receiver**
   - **Thermal stabilization:** Additional thermal stabilization for modem components will improve stability in outdoor experiments (see below).
   - **Closed-loop beam tracking:** Implement tracking loops transceivers to speed up link acquisition and improve link stability. Leverages parallel program efforts at TSC

3. **Option 1**
   - **Narrowband filter for wide FOV data and acq/track receivers**

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# Cloud Measurements Support Receiver Design

- ## Phase 2 Objectives

  - ### Develop and demonstrate a robust ASE receiver system

    - ASE modem requirements matched to optimum receiver design and scattering phenomena

    - Identify optimum acq/track receiver configuration

    - Design hybrid data receiver: *large* FOV/*low* bandwidth and *low* FOV/*high* bandwidth capabilities

- ## Determine scattering function

  - ### Intensity vs FOV, angle and position *in cloud*

  - ### Correlated to optical thickness (LOS attenuation)

  - ### As though cloud were thick slab
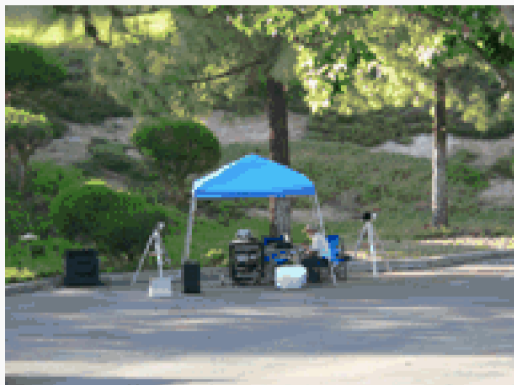
- ## Estimate properties of extended source in typical link scenarios

  - ### Extent of emitting surface

  - ### Angular & spatial distribution of emission

  - ### Pulse broadening inside cloud >> outside cloud

Measurements:

Tx

Wind

Rx

Analysis:

Tx

Cloud Thickness

Link Distance

FOV

Rx
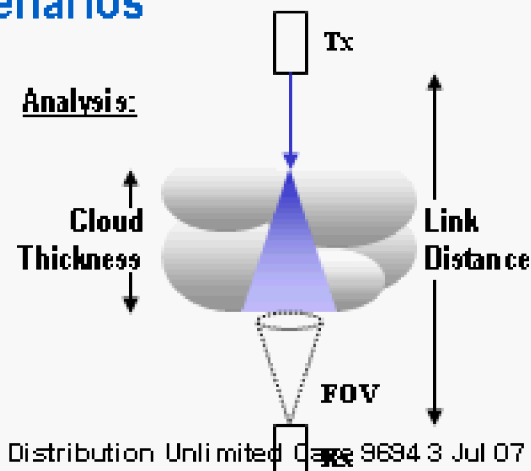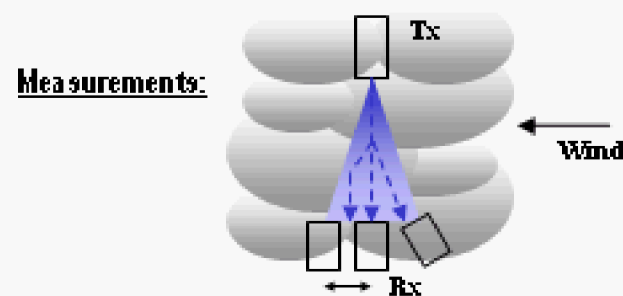
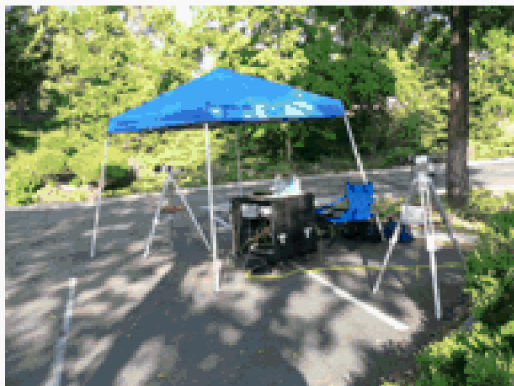# ORCLE Equipment Check-out


Transmitter site


Receiver A with Aspheric Objective


Transmitter collimator


Receiver site


Receiver E with Fresnel Objective


Receiver equipment

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